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TERMINATED EXPLODING WIRE ENERGY SOURCE

By Louis A. Rosenthal*

ABSTRACT: By placing a discharge or "dump" tube across an exploding bridgewire load, it is possible to by-pass the electrical energy and terminate the explosion of the wire. The dump tube is triggered by a signal derived from the energy removed from the storage capacitor.

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This report describes an apparatus developed to terminate at selected, settable times the energy input to an exploding bridgewire (EBW). The apparatus should prove useful to those engaged in EBW studies. In particular, it should be of benefit in determining the importance of various portions of the energy pulse in effecting detonation of an explosive surrounding the EBW.

The work was carried out under Task RUME 4E-000/212-1/F008-08-11, Problem Assignment No. 019, Analysis of Explosive Initiation.

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By direction

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INTRODUCTION

In the study of exploding wires for the initiation of explosive devices, it was deemed desirable to terminate the energy discharge into the exploding wire at a predetermined point. Thus, for example, by terminating the bridgewire explosion prior to the plasma phase the significance of this phase in causing detonation of a surrounding explosive could be determined. Similarly, by stopping the energy input at some point in the superheating phase, the wire explosion is "forced" at a reduced energy level. The theory and application of a technique for accomplishing this energy dump will be described. It is primarily intended for exploding bridgewire systems as employed in electroexplosive devices, but, of course, can be extended to other systems.

ANALYSIS AND THEORY

Consider the basic exploding bridgewire circuit shown in Figure 1. The prime components are an energy storage capacitor, C_0, a series switch device, and an EBW load. A voltage divider and current viewing resistor are included so that EBW voltage and current can be monitored by means of a cathode ray oscillo- scope. The series switch can be of the spark gap or gaseous variety and is fired from an external trigger signal. The dump tube (or dump switch) is placed across the EBW load as shown. Since the load would generally be supplied through a length of cable in going into the firing chamber or equivalent enclosure, it is very desirable to place the dump tube directly across the EBW. For a switch to be effective it is obvious that it must offer a very low impedance on closure.

The start trigger fires the series switch (GL 7964-1 G.E. Triggered Spark Gap Tube) which was chosen because of its high reliability, high voltage and current capability, and "clean" switch action. It can conveniently be placed in series with the load and triggered via a pulse transformer. The dump tube selected is a cold cathode gas tube* which requires a positive trigger grid signal to fire. Other combinations of tubes may be satis- factory. After the start trigger there is an ionization delay in the series switch tube of the order of 1.5 μs with a small associated jitter. The dump tube also has a delay in the order of 0.5 μs. Unsuccessful attempts were made to fire in sequence the series tube and then the dump by means of a variable delayed pulse[1**]. The jitter and trigger variables, however, were too large to attain the required firing accuracies. It was expected that a typical maximum dump time of 1 μs and position (time) control to 0.1 μs were achievable.

* KP 130B, Kip Electronics, or KN 6, Edgerton, Germeshausen and Grier.

**References may be found on page 9.

A very simple technique based on integrating a discharge pulse waveform evolved. As shown in the basic circuit, the dump tube grid is driven by a simple integrating network. This network is integrating the load voltage right after the series switch fires. When the integrated voltage reaches a firing level (i.e., 300 v) the dump tube will fire. Thus the dump is delayed from the start by an amount which depends on the integrated voltage at point A and the trigger level for the dump tube. However, for any experiment it is possible to control the dump time position by adjusting the time constant RC. Starting with a large RC and going down to shorter times, the dump tube will go from an off state to a fast or early dump. By trial, the appropriate dump location is obtained. This is an extremely simple method which gives very accurate and reproducible timing. If the voltage at point B is sensed (right across the EBW) then the voltage levels are low and, in many cases, insufficient to reach the firing level for the dump tube.

If the initial voltage on the storage capacitor (C_0) is V_0 then after switch closure it will fall according to

$$v_t = V_0 - \frac{1}{C_0} \int i dt \tag{1}$$

where "i" is EBW current. The loading offered by the integrating network is negligible and the integrating time constant is typically large compared to the time to dump. Thus if integrator error is ignored

$$V_g = \frac{1}{RC} \int_0^t v_{(t)} \, dt \quad . \tag{2}$$

Assuming that an exploding wire current is limited by the discharge inductance (L) in the initial regions according to $i = (V_0/L)t$, then the capacitor voltage would follow

$$v_{(t)} = V_0 - \frac{1}{C_0} \frac{V_0}{L} \frac{t^2}{2} = V_0 \left[1 - \frac{t^2}{2LC_0}\right] \quad . \tag{1a}$$

This wave shape is typically observed. Upon integration according to equation (2)

$$\begin{aligned} V_g &= \frac{V_0}{RC} \left[t - \frac{t^3}{6LC_0}\right] \\ &= \frac{V_0}{RC} t \left[1 - \frac{t^2}{6LC_0}\right] \quad . \end{aligned} \tag{3}$$

The deviation from linearity is related to the natural ringing period $T_r = 2\pi \sqrt{LC_0}$ and the rate at which energy is removed from the capacitor. In experiment, a linear ramp is observed up to the firing point of the dump tube. If the firing voltage for the tube is, for example, 250 volts and V_0 is 2500 volts then the trigger time t_f is

$$t_f = 0.1\ RC \quad .$$

Actually a delay time must be added to this to obtain the true firing time. It must also be noted that the 250 volt firing level can vary with the actual anode voltage available. Thus it is not possible to precalibrate R in the integrating network for dump timing. For any given set of conditions, decreasing R will advance the firing time in a continuous manner.

The dump tube must offer a low resistance and inductance to the EBW at any point in its explosion cycle and so shunt the current and terminate the energy input. Depending on the wire state, the wire may offer negligible impedance and make dumping impossible. The wire voltages are likewise low and the dump tube will not be able to fire prior to a wire change of state. Ignoring the important inductances, if the tube of resistance, r_d, shorts the bridge (R_B) resistance, as shown in Figure 2a, the line current (i_L) is split according to

$$i_B = \frac{r_d}{r_d + R_B} \cdot i_L \quad .$$

A small r_d will divert the current from the bridgewire and change the character of the line current i_L since the load impedance for C_0 is now significantly reduced.

It is practically impossible to avoid inductance in the leads to the EBW and in the dump tube itself. As one tries to achieve a faster current dump, the finite inductance becomes more significant according to L di/dt. During dump, current changes of 10^{10} amps/sec are observed and a small inductance can produce a significant reaction at these rates. In order to examine some of the dump restrictions the circuit of Figure 2b, including inductances, will be analyzed for certain line current wave shapes. The general equation to be solved for $t > 0$ after closing S_1 is in LaPlace transform notation:

$$i_B(s) = \frac{(r_d + SL_d)\ Li_L(s)}{r_d + R_B + S\ (L_d + L_B)} + \frac{L_B i_B(0)}{r_d + R_B + S\ (L_d + L_B)} \quad . \qquad (4)$$

In this equation the first term represents the line current split and the second is the decay of the initial EBW current level $i_B(0)$. If the line current is a constant I_L and steady state is reached in the EBW arm ($i_B(0) = I_L$) then the solution for equation (4) in the time domain is

$$i_B(t) = \frac{r_d I_L}{r_d+R_B}\left[1- \frac{T_D-T_1}{T_1}\, e^{-t/T_1}\right] + \frac{L_B I_L}{L_d+L_B}\, e^{-t/T_1} \tag{4a}$$

where $T_D = L_d/r_d$ and $T_1 = \dfrac{L_d+L_B}{r_d+R_B}$;

two time constants. The first term of equation (4a) will indicate the steady state split after S_1 is closed by letting $t \longrightarrow$ approach infinity. The second term is the decay of the initial value of EBW current. It is of interest to note that as long as there is an inductance in the dump arm (L_d), there will be a initial drop in EBW current according to L_B/L_d+L_B. This change results in an impulsive voltage across the parallel circuit and indicates a continuity of flux linkages. An impulsive voltage change (dv/dt = infinity) can result in an oscillation burst in the observed voltage waveform traces. In many cases the distributed capacity across the EBW will suppress this transient. When the L_d term is ignored the behavior is simpler in concept in that the initial I_B decays to a new value with an equivalent time constant T_1. A sketch of the theoretical EBW current waveform is shown in Figure 2c. The significance of inductance in the dump circuit is noteworthy.

As another example of the theoretical aspects of dumping the energy, consider a ramp current waveform of the form

$$i = \frac{V_o}{L}\, t = \alpha t \quad .$$

This would correspond to the initial portion of the capacitor discharge circuit where V_o is the initial capacitor voltage. Let the EBW current at t=0 be I_o, as an initial condition. The solution is now

$$i_B(t) = \frac{r_d}{r_d+R_B} \cdot \alpha\left[t + (T_D-T_1)(1 - e^{-t/T_1})\right] + \frac{L_B I_o}{L_d+L_B}\, e^{-t/T_1} \quad . \tag{5}$$

It is apparent that the best dump results from $r_d \longrightarrow 0$ (also $L_d \longrightarrow 0$) and this short circuit still allows the EBW current to fall as

$$i_B(t) = I_o e^{-\frac{R_B t}{L_B}} \quad . \tag{5a}$$

A sketch of equation (5) is shown in Figure 2d and the ramp current rise can appear in R_B if the dumping is not efficient.

There are many practical considerations which upset the ideal theoretical picture. The current drive source is not constant (i.e., high impedance) which means that if the parallel combination of EBW and dump suddenly offers a low impedance the current will change. Actually this does not appear to be too significant since the series inductance "L" does dominate the discharge impedance circuit. The circuit damping may change for the subsequent discharge (even to the point of oscillation). However, prior to dump the EBW explosion process did not offer a very large reaction on the current.

A very significant factor is the change in R_B with current. Whereas one could assume a nearly constant r_d associated with the gaseous discharge tube the exploding bridgewire itself (R_B) is going through tremendous resistance changes. Consider the EBW in the superheated phase wherein the magnetic pinch forces are physically keeping the structure in shape. As soon as the current is reduced, or by-passed, the pinch forces release since they vary as I^2, the superheated column expands increasings its R_B. This unstable condition will result in R_B rapidly increasing to infinity and transfering all of the energy to the dump tube. It could be considered that dumping has precipitated or "forced" an explosion by removing the constraining magnetic forces. Once the wire goes into the plasma phase then the dump tube will generally act as a good short since it represents a confined controlled discharge path.

To illustrate this effect of an increasing R_B consider a perfect dump ($r_d = 0$ $l_d=0$) applied to an EBW passing a current I_0. The current decay will be

$$i_B = I_0 e^{-\frac{R_B t}{L_B}} \quad .$$

Now assume that the EBW has a characteristic typical of an arc so that $v_B i_B = K$ where v_B is the bridgewire voltage drop (at current i_B). At the start of the dump let the bridgewire resistance be R_B (static value). Now K can be evaluated as

$$K = I_0^2 R_B \quad \text{and}$$

$$v_B = I_0^2 R_B / i_B \quad . \tag{6}$$

This equation describes the opening up of the EBW as $i_B \longrightarrow 0$ giving rise to an infinite voltage. If the discharge or dump equations are solved then

$$(i=i_B) \qquad L\frac{di}{dt} + I_0^2 R_B / i = 0 \quad . \tag{7}$$

The solution is

$$i = I_0\sqrt{1 - \frac{2R_B t}{L}} \qquad (8)$$

which shows a decrease to zero (0) in the finite time ($t_0 = L/2R_B$) of half a time constant. Although both circuits start their current decay at the same rate of $di/dt = -I_0R_B/L$ the increase of resistance R_B with a decrease in i_B results in a current "dive". The EBW circuit inductance has been considered constant in this analysis.

Thus there are several problems associated with a fast dump. It is true that a perfect short circuit would be the best choice at which time the EBW inductance still limits the energy and rate of removal. This energy is $1/2\ L_BI_B^2(0)$ and should be kept as small as is possible. The leads which connect the EBW to the dump tube provide the greatest portion of L_B.

APPLICATION

To apply the concepts introduced, the design of a practical exploding wire energy source with the energy termination or dump will be presented. Several typical waveforms will compare the practical with the theoretical.

Figure 3 is a complete EBW firing set. The upper region is the high voltage charging circuit and the lower region is the firing and triggering circuitry. A commercial prepackaged power supply provides 0-5000 volts by variac control. A voltmeter circuit is across the supply. The 1 mfd (5 kv) energy storage capacitor is charged through a series 5 megohm resistor. A neon tube across 1 megohm of the series resistor string acts as a charge indicator. The light goes out when the charging current drops below 50 ua. The series switch tube is a triggered spark gap tube (GE #7964) pulsed through an isolation pulse transformer designed for this task.

The transformer will be pulsed by means of an auxiliary thyratron circuit. This circuit has its own power supply which provdes 325 v to charge a 0.25 mfd capacitor via a 1 megohm charging resistor. The 2D21 thyratron acts as a shunt switch which when fired throws the charged capacitor across the primary of the trigger pulse transformer. A 1k resistor across the primary dampens out any oscillation and provides for a fast charge path. To fire the thyratron a direct trigger signal can be injected into the grid from some external source (i.e., camera, remote fire). A circuit is also provided for an internal trigger pulse. The "press to fire" switch provides a clean delayed pulse when actuated. This pulse is available as a synch out signal if desired. There is significant delay (10 us) between the thyratron trigger pulse and the firing of the main series switch. It appears that the pulse transformer gives a ringing pulse output and is a prime source of jitter and delay.

The output of the firing circuit appears at an output jack which will supply the EBW through a few feet of cable depending on the physical layout of the experiment. Since 50Ω RG 9/u cable has an inductance of close to 0.081 uh/ft, a typical length of 8 ft can provide 0.644 uh. This inductance, plus the internal inductance of the capacitor and wiring, limits the rate of current discharge. The electrical characteristics of this type of firing unit have been described[8]. The signal at the output jack is passed through a 1k fixed and a 5k variable series resistance on to an integrating capacitor. This capacitor can be a fixed mica, low loss, variety or the cable capacity (at 30 pf/ft) which will feed the dump tube on a remote chassis. This chassis would generally be located in an explosive firing chamber and would contain a current viewing resistor and a voltage divider network. The dump tube must be physically located close to the EBW terminals. It must be shielded from any shock and debris. It is necessary to supply a keep-alive current to this cold cathode triggered discharge tube. This is accomplished through 41 megohms of current limiting resistance. The delay time for the energy termination must be arrived at by selecting C and the variable 5k resistor. Some waveform observations will indicate the circuit performance.

EXPERIMENTAL OBSERVATIONS

A typical dump time delay characteristic is shown in Figure 4. The load was a fixed resistor of 4.5 ohms for this case. It would be expected that this characteristic would change depending on the EBW characteristic. Not only would the capacitor voltage vary differently as the EBW energy varies, but, in addition, the dump tube voltage depends on the EBW phase. For example, when the wire explodes the large L di/dt prior to the plasma phase can break down the dump tube if its firing level is not high enough. For a particular test set-up there is some unique firing delay characteristic. Note that there appears to be a minimum time in the order of 0.35 us, This is related to the firing or ionization time of the dump tube.

Several traces will be shown and described in terms of the theory discussion. Figure 5a shows the dumping of energy away from a 0.9 ohm resistor. Sweep is 1 us/cm and the current is 400 amp/cm. A 1 cm square is shown for reference scaling. Without the dump, the circuit discharge is nearly critically damped. Roughly two-thirds of the current is diverted indicating a dump tube resistance of about 0.45 ohms. It is of interest to note that the dump tube has resulted in lower energy dissipation thus leaving more energy for the reverse cycle during which the dump tube is probably out. It was not possible to dump a short circuit and dumping efficacy depends on the relative resistance levels of the dump tube and the instantaneous EBW resistance.

Figure 5b is again at 400 amps/cm but at a sweep speed of 0.2 us/cm. The top trace is the current through a 0.9 ohm resistor and the bottom trace is for a 4.5 ohm resistor. Note that the discharge rate is much faster as the dump time constant is decreased, assuming a constant inductance in the dump loop. The current in the 0.9 ohm case does not go to zero due to the expected current split. Several of these discharges superimposed indicated a jitter maximum of ± 0.025 us.

Figure 5c shows the dump characteristics when the EBW is an exploding gold wire. The level is 400 amp/cm at 0.2 us/cm, as in the previous case. The top trace is for no dump and the explosion has only resulted in an inflection in the current trace. Obviously there is an excess of capacitor energy available. The next trace is arranged to dump during burst. Clearly the opening of the wire and its increasing resistance have aided the dumping action. In the bottom or last trace, the dump has been delayed to the plasma phase and the dumping is considerably poorer. Part of the inflection is still evident and only the post explosion characteristic is changed. It would be increasingly difficult to dump in the pre-explosion region as the EBW resistance is at its lowest values. However, no difficulty was observed in dumping at levels which almost eliminate the characteristic explosion.

The traces of Figure 6 are for a gold wire and include voltage and current waveforms for various dump delays. The voltage traces (lower) at 1600 v/cm and current (top) at 400 amp/cm are synchronized in time and obtained on a dual beam oscilloscope. Sweep times are at 0.2 us/cm for this case of a 2 mil-diameter, 75-mil long wire. The dump time is shortened from the top left trace to the bottom right trace. At early dump the characteristic voltage peak has essentially disappeared.

Figure 7 contains the same sequence of traces for platinum wire which is 2-mil diameter and 50-mil long. The characteristic state change in the platinum wire, as evidenced by a plateau region, is clearly visible. In this set of traces the vertical sensitivity is at 800 volts/cm, the current is at 200 amp/cm, whereas the sweep time is 0.2 us/cm.

These traces indicated the degree of control possible. It remains to apply the apparatus and interpret the importance of these various EBW regions in explosive initiation.

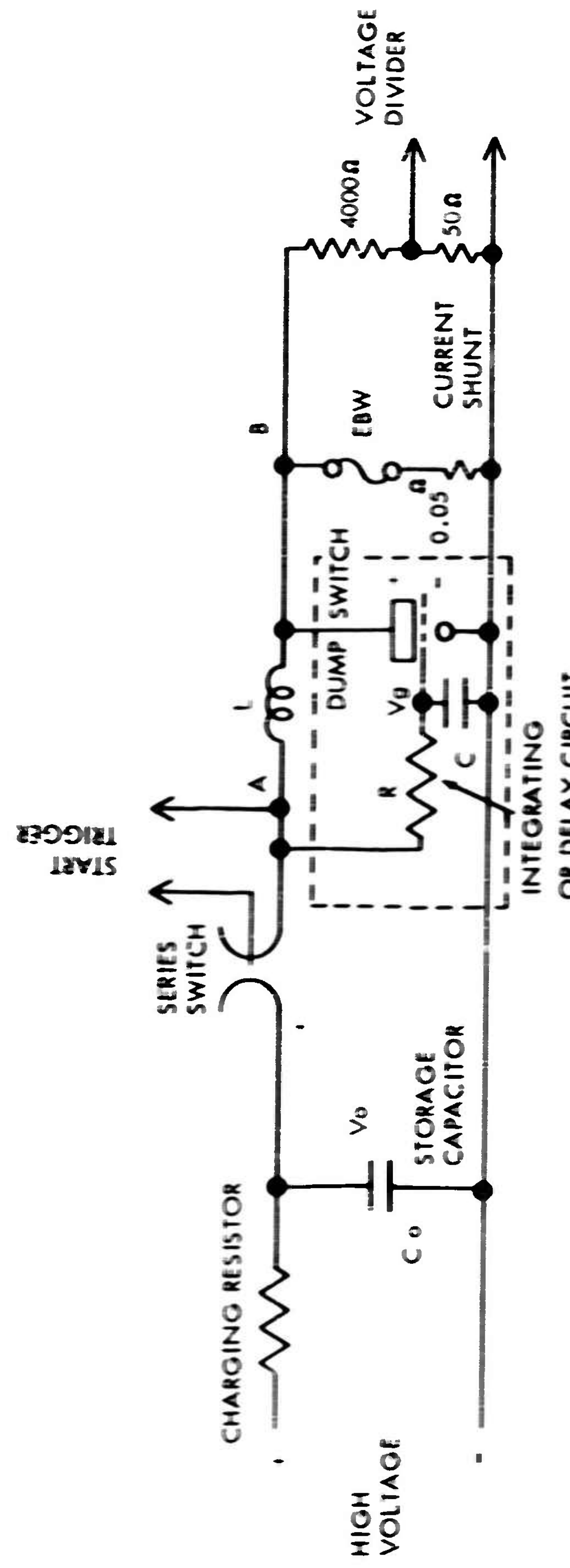

FIG. 1 THE BASIC DISCHARGE AND DUMP CIRCUIT

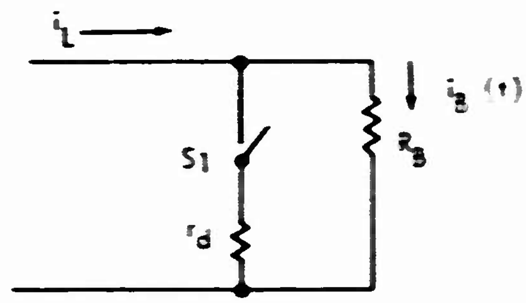

FIG. 2a. SHORTING OF BRIDGE WIRE, R_B, BY DUMP TUBE RESISTANCE, r_d, IGNORING INDUCTANCE

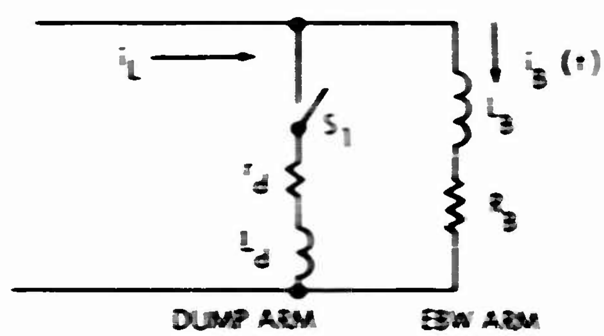

FIG. 2b. SHORTING OF BRIDGE WIRE BY DUMP TUBE WITH INDUCTANCE PRESENT

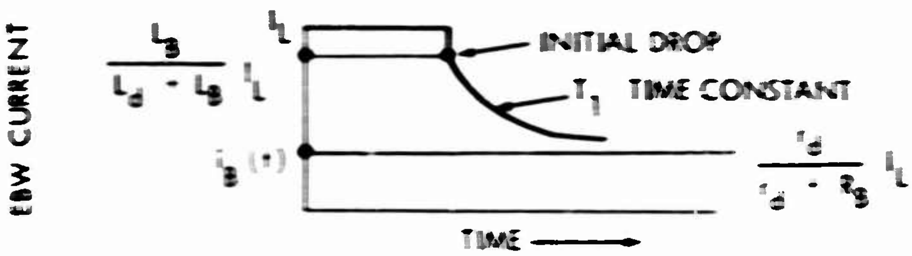

FIG. 2c. EBW CURRENT VS TIME FOR STEP CURRENT INPUT AND DUMP

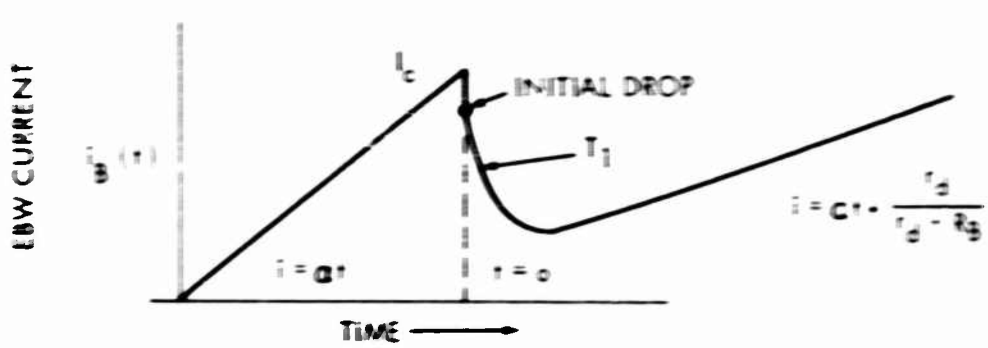

FIG. 2d. EBW CURRENT VS TIME FOR RAMP CURRENT INPUT AND DUMP

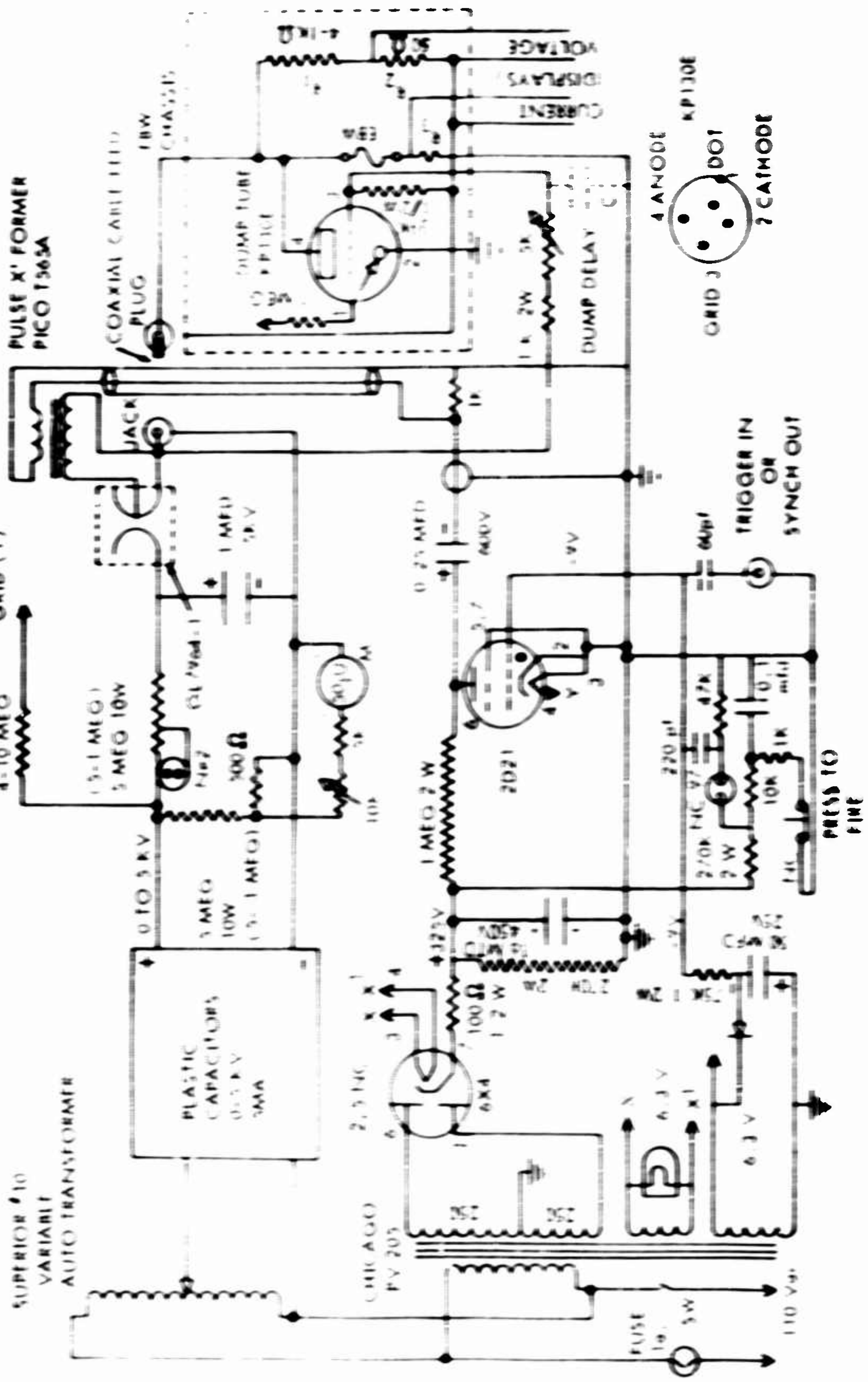

FIG. 3 EXPLODING BRIDGE WIRE FIRING UNIT WITH DUMP FACILITY

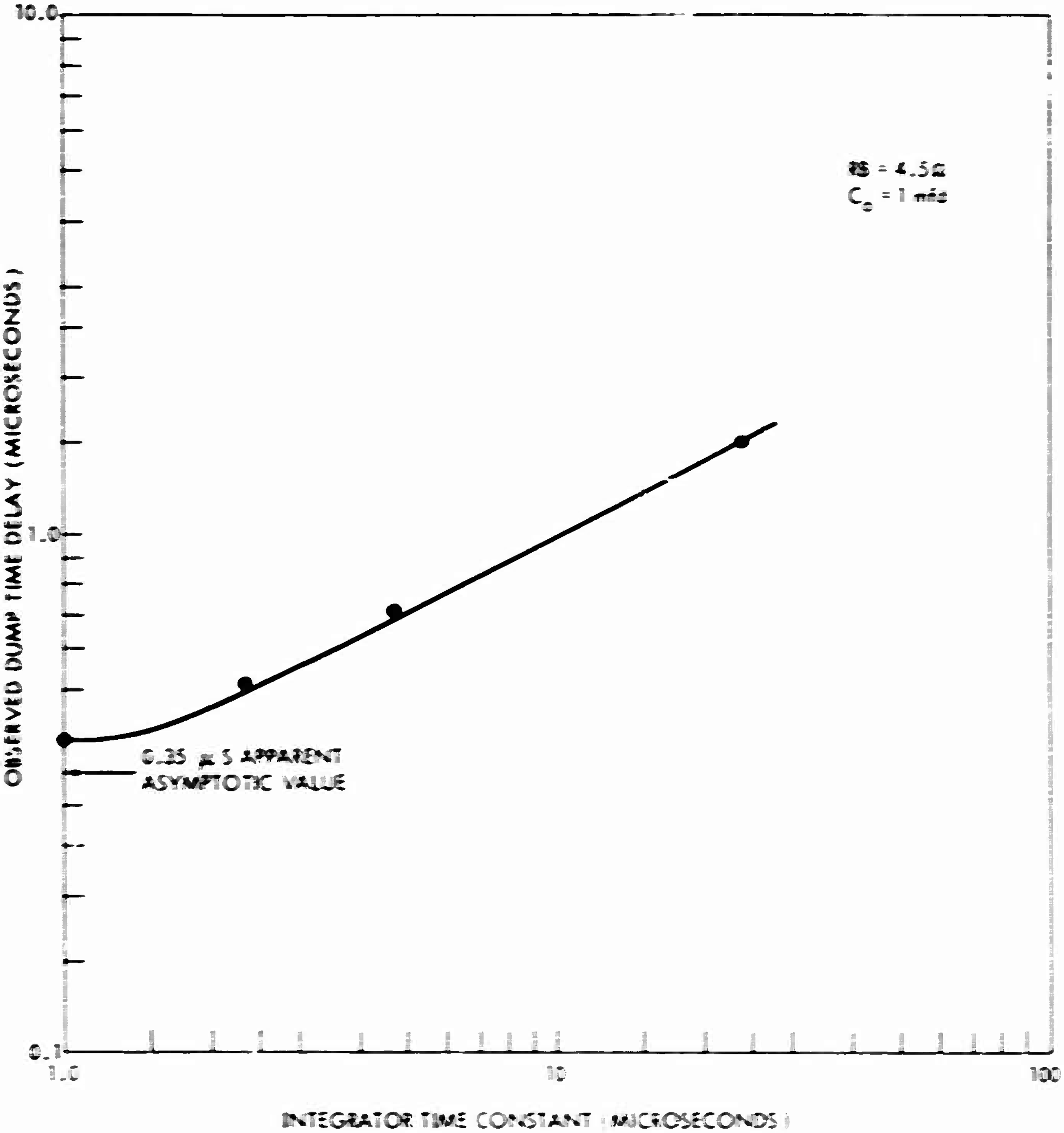

FIG. 4 DUMP TIME DELAY VS INTEGRATOR TIME CONSTANT FOR A LOAD OF 4.5 OHMS

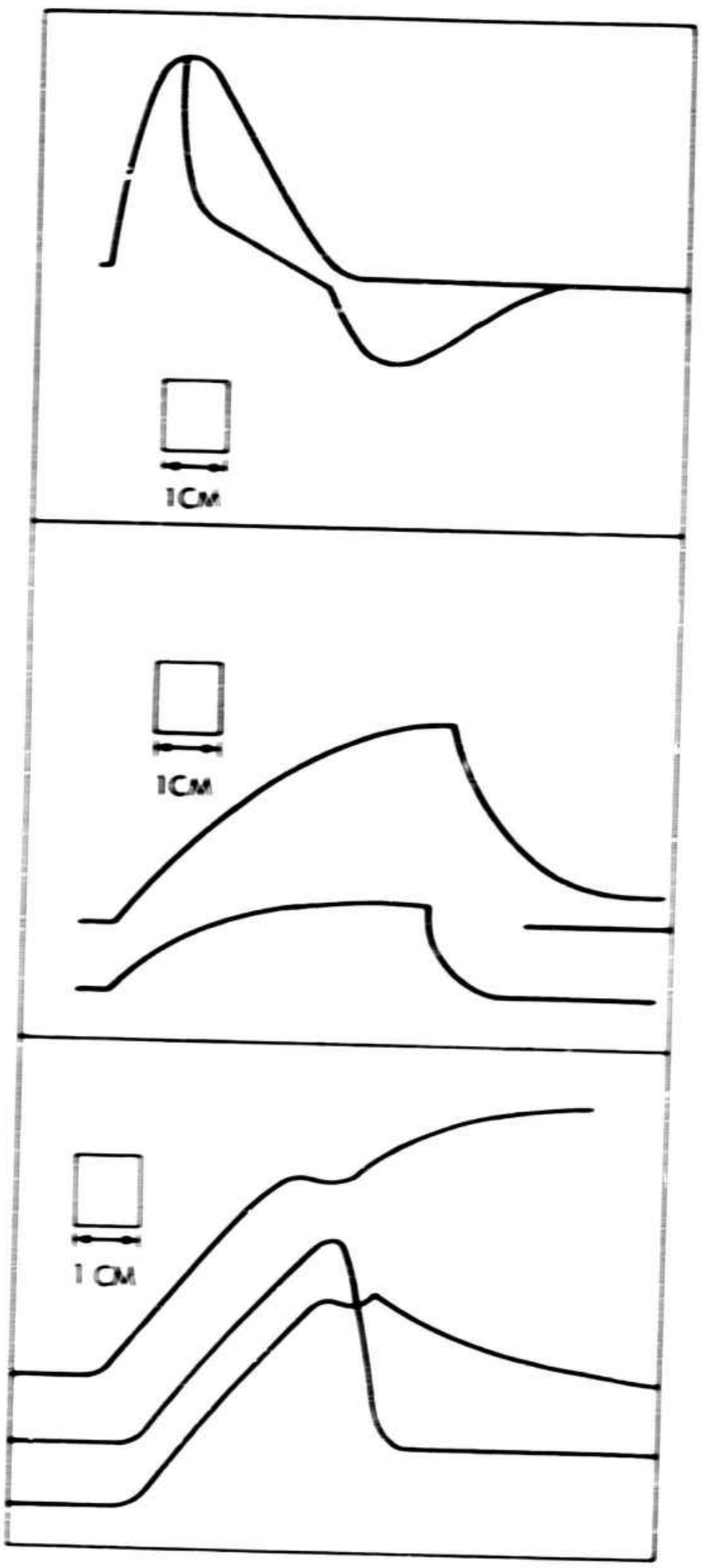

FIG. 5a CURRENT WAVEFORMS WITHOUT DUMP (UPPER TRACE) AND WITH DUMP USING A 0.9 OHM LOAD RESISTOR. (SWEEP 1 μ SEC/CM, CURRENT 400 AMP/CM)

FIG. 5b ENERGY DUMP USING 0.9 OHM (UPPER) AND 4.5 OHM LOAD RESISTORS. (SWEEP 0.2μSEC/CM, CURRENT 400 AMP/CM)

FIG. 5c DUMP CHARACTERISTICS FOR A GOLD EBW. UPPER TRACE NO DUMP. LOWER TWO TRACES SHOW DUMP DURING BURST. (SWEEP 0.2μSEC/CM, CURRENT 400 AMP/CM)

FIG 5

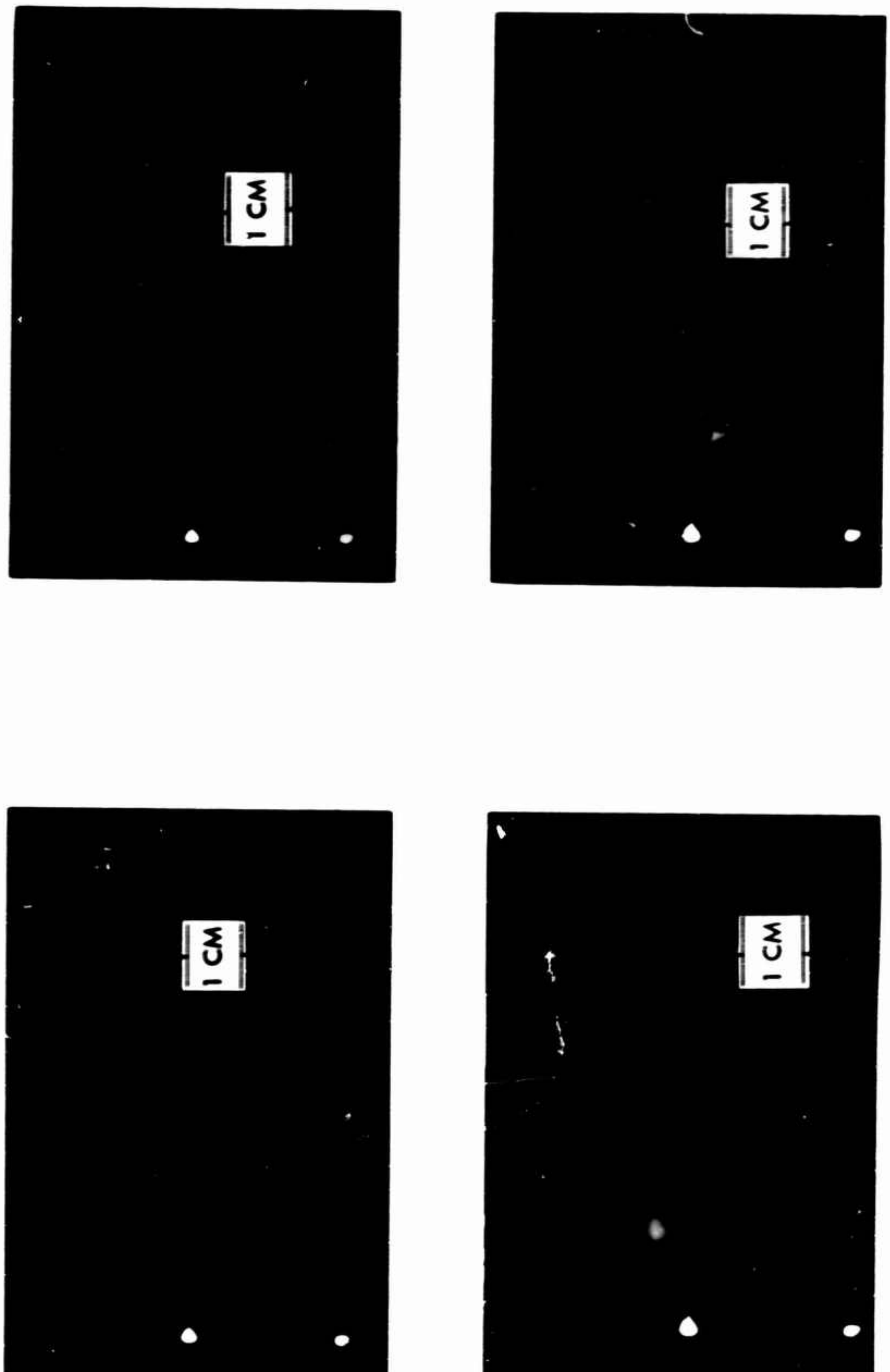

FIG. 6 CURRENT (UPPER) AND VOLTAGE WAVEFORMS FOR VARIOUS DUMP DELAYS INTO A 2-MIL DIAM. BY 75-MIL LONG GOLD WIRE. (POTENTIAL 1600 V/CM, CURRENT 400 AMP/CM SYNCHRONIZED SWEEP 0.2 μ SEC/CM) DUMP TIME DECREASES FROM TOP LEFT TO BOTTOM RIGHT.

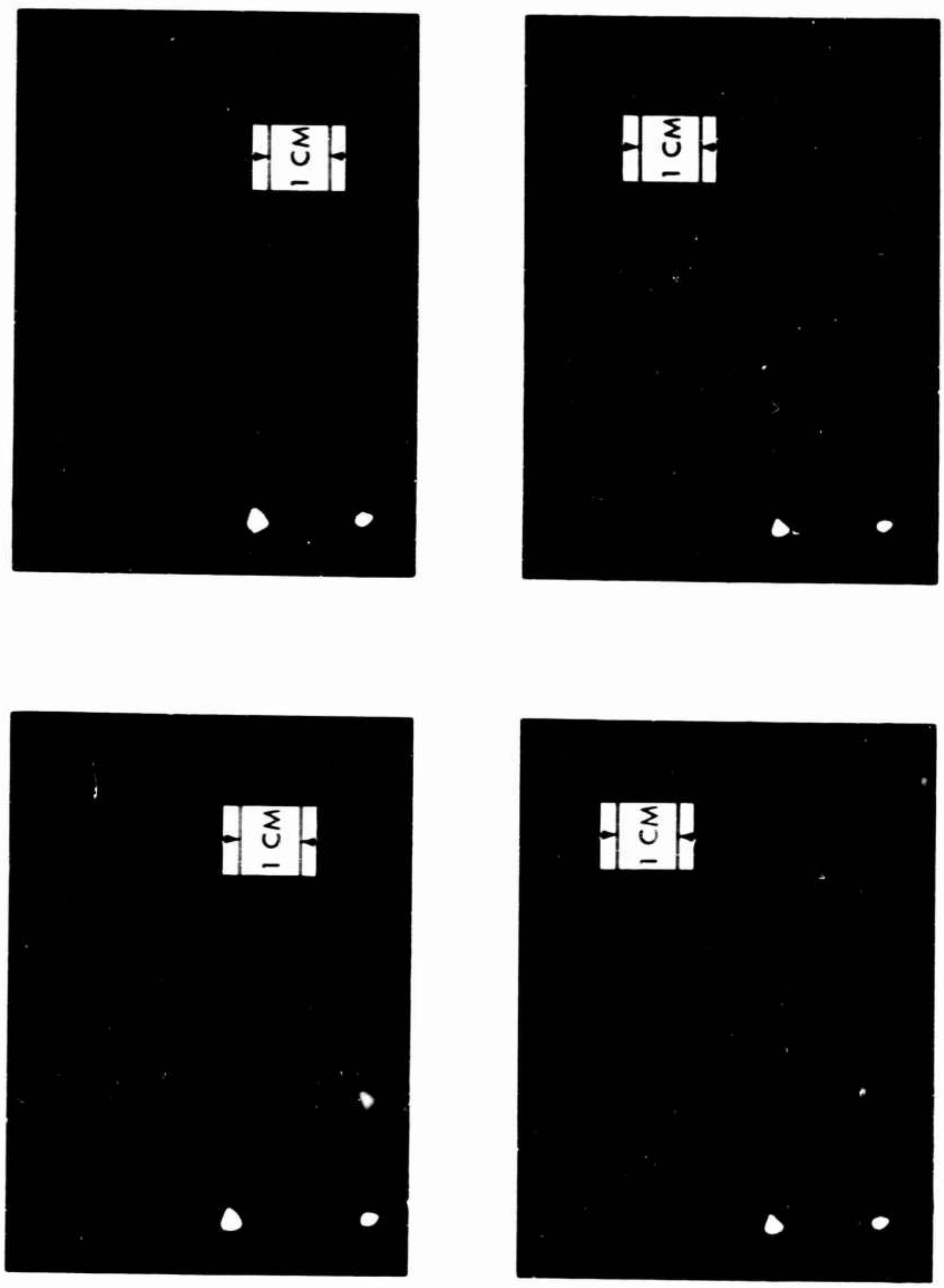

FIG.7 CURRENT (UPPER) AND VOLTAGE WAVEFORMS FOR VARIOUS DUMP DELAYS INTO A 2-MIL DIAM. 50-MIL LONG PLATINUM WIRE. (POTENTIAL 800 V/CM, CURRENT 200 AMP/CM, SWEEP 0.2μ SEC/CM) DUMP TIME DECREASES FROM TOP LEFT TO BOTTOM RIGHT.

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